VALIDATION OF PEDESTRIAN UPPER LEGFORM IMPACT TEST - RECONSTRUCTION OF PEDESTRIAN ACCIDENTS

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ABSTRACT

EEVC/WG10 proposed three component pedestrian subsystem tests. Euro-NCAP pedestrian tests have been conducted according to these procedures. The results from Euro-NCAP indicate that the upper legform impact test has the most difficulty fulfilling the current injury criteria. However, the number of severe injuries from impact against the bonnet leading edge has been decreasing recently.

The objective of this research is to validate the test conditions and injury criteria of the EEVC upper legform impact test from accident analyses, impact tests with production cars and accident reconstruction tests.

The top four factors affecting the injury risk of the femur/pelvis were the bonnet leading edge height, the pedestrian age, the vehicle registration year, and the bumper lead. The fracture of lower leg also affected the significance of the upper leg injury.

The Weibull cumulative frequency curve was obtained as a biomechanical injury risk curve from accident reconstruction tests. At the 50 percentile injury risk level, 7.5 kN for impact force and 510 Nm for bending moment were obtained. The current injury criteria of 4 kN for impact force and 220 Nm for bending moment are too severe.

It is necessary to reconsider the injury criteria and test conditions of the EEVC pedestrian upper legform impact test.

INTRODUCTION

Pedestrians are vulnerable road users. Pedestrian casualties are still a major concern in traffic accident safety in European countries, the USA, Australia and Japan. European Experimental Vehicles Committee (EEVC), National Highway Traffic Safety Administration (NHTSA), International Standard Organization (ISO), and International Harmonized Research Activity (IHRA) have been conducting research to propose a pedestrian test procedure reflecting real-world pedestrian accidents.

The EEVC/WG10 [1] proposed three component subsystem tests, the headform impact against the bonnet, the upper legform impact against the bonnet leading edge and the legform impact against the bumper, as shown in Figure 1.

Recently, pedestrian impact tests with production cars have been conducted in Euro-NCAP tests according to the current EEVC subsystem test method. The results from the Euro-NCAP tests indicate that none of the cars tested fulfills the current requirements of the three EEVC subsystem tests. The upper legform impact test seems to have the most difficulty fulfilling the requirement among the three tests. However, recent accident analyses indicate that the priority of the upper legform impact test seems to be the lowest in the three EEVC subsystem tests.

Accordingly, we conducted pedestrian accident analyses, impact tests with production cars and accident reconstruction tests to validate the EEVC upper legform impact test. This report summarizes the results of the accident analysis and the impact tests and proposes new injury criteria for the upper legform impact test.

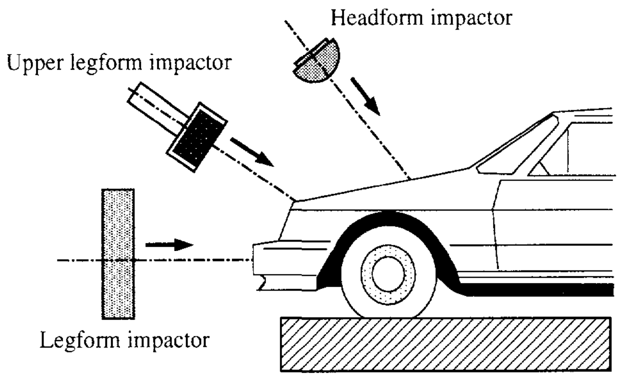


Figure 1. EEVC subsystem tests.

PEDESTRIAN ACCIDENT DATA ANALYSIS

Current Situation of Pedestrian Accident

Pedestrians are often involved in traffic accidents. In Japan in 1997, pedestrian fatalities (persons who died within 24 hours) represented 27 % (2,643 persons) of the total fatalities (9,640 persons) in traffic accidents [2].

In fatal pedestrian accidents the most severely injured parts of the body are the head/face/neck (64%) and the chest (12%); in nonfatal accidents they are the leg (40%) and the head/face/neck (32%), as shown in Figure 2.

In more than 50% of the fatal and nonfatal pedestrian accidents, pedestrians are hit by passenger cars [3]. Constitution ratios of the body region with AIS 2+ have changed drastically during last ten years as shown in Figure 3. In particular, femur injuries decreased from 17% to 4% and knee injuries, from 10% to 1%. During the same period, chest injuries increased from 3% to 11% and lower leg injuries, from 19% to 36%.

Constitution ratios of car parts causing AIS 2+ injury have also changed during the last ten years as shown in Figure 4 in which others include front spoiler, license plate, and front grill. The ratio of the car parts, such as front bumper and others, related to the lower leg injuries increased from 45% to 55%. The ratio of the car parts, such as windshield, frame, and A pillar, related to head injuries also increased from 13% to 21%. In contrast, the ratio of the leading edge of bonnet and wing related to femur/pelvis injuries decreased from 17% to 8%. The ratio of top surface of bonnet and wing decreased from 26% to 16%.

When we consider the current situation of pedestrian accidents, the highest priority should be head protection followed by lower leg protection. The upper legform impact test related to the femur/pelvis injury is the lowest priority among the EEVC pedestrian subsystem tests.

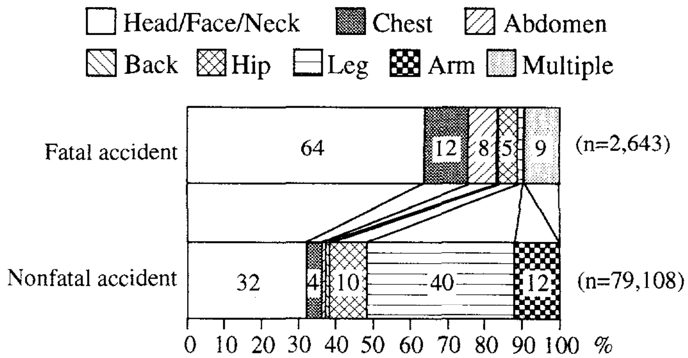


Figure 2. Body regions with most severely injured. (1997 in Japan [2])

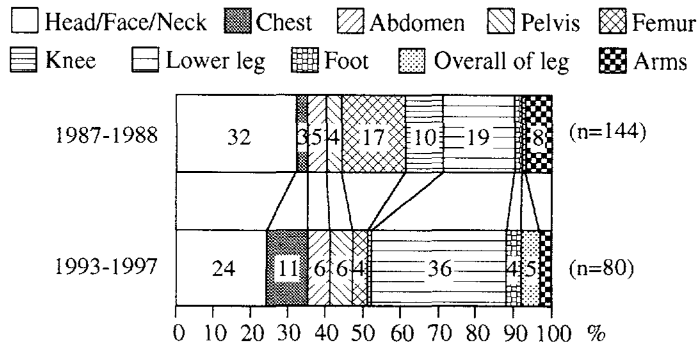


Figure 3. Body regions with AIS 2+ injury in passenger car [4].

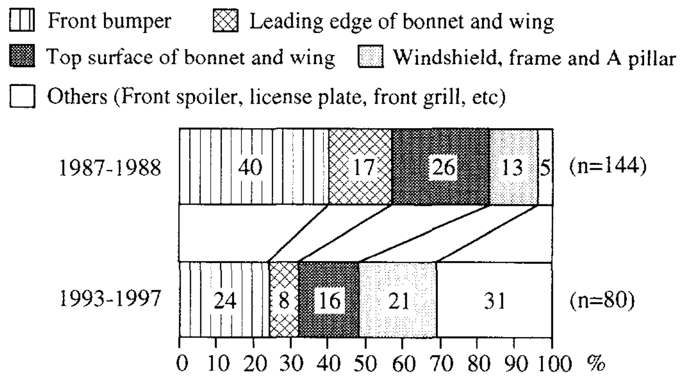


Figure 4. Car parts causing AIS 2+ injury [4].

In-depth Analysis on Femur/Pelvis Injuries

The JARI pedestrian accident data base was used to analyze femur/pelvis injuries caused by the leading edge of the bonnet or wing. The data base consists of 121 pedestrian accident cases from 1987 to 1988. A total of 54 cases with contact mark or residual deformation on the leading edge was selected. All pedestrians were adults (16 years and older) and children taller than 150 cm.

<u>**Injuries Selected**</u>

The selected 54 cases consisted of 30% for AIS 2+, 35% for AIS 1 and 35% for no injury as shown in Figure 5. For AIS 2+ injury, 81 % of the cases involved femur, pelvis or lumbar vertebra fractures as shown in Table 1.

Cumulative frequencies of the impact velocity were obtained for the two different injury severities as shown in Figure 6. There is no significant difference between the two curves. The difference is only 5 km/h at the 50 percentile. The impact velocity does not seem to be major factor in causing femur/pelvis injuries.

<u>**Influence of Vehicle**</u>

The contact locations of the leading edge of bonnet and wing are divided into five areas as shown in Figure 7. Pedestrians tend to impact at the front left side (18 cases) rather than at the front right side (12 cases) as shown in

Figure 8. Note that in Japan vehicles run on the left side and drivers sit on the right side. This results may be opposite in most of the European countries and the USA.

The possibility of contacting the leading edge of the wing was relatively high in spite of its small area.

Accident cases with AIS 2+ distributions of the contact location were similar to the previous results as shown in Figure 9.

The risk of severe injuries of AIS 2+ was higher in the area of the wing (A) than in the bonnet area (B and C) as shown in Figure 10.

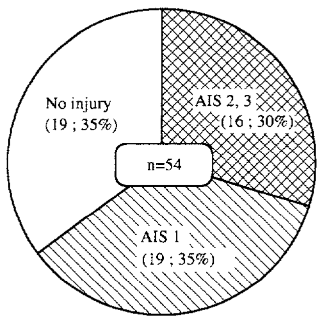


Figure 5. Constitution ratio of injuries caused by leading edge of bonnet or wing.

Table 1.
Description of AIS 2+ Injuries for Femur/pelvis

Injury (n=16)		case	%
Fracture of	Femur and pelvis	2	13
	Femur	5	31
	Pelvis	4	25
	Pelvis with abdominal injury	1	6
	Lumbar vertebra	1	6
Abdominal injury		3	19

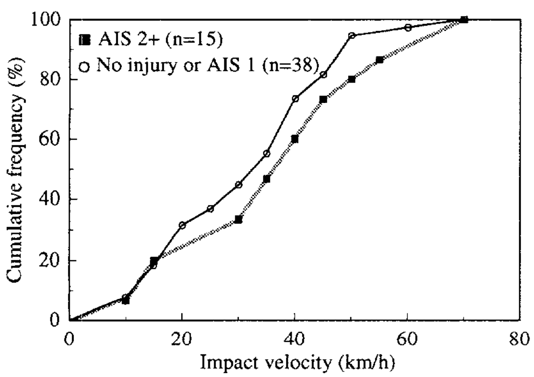


Figure 6. Cumulative frequency of impact velocity.

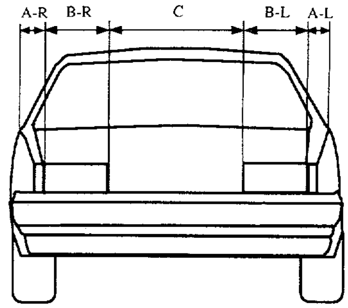


Figure 7. Definition of contact locations.

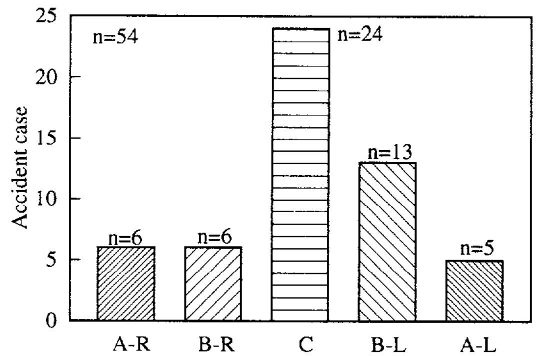


Figure 8. Distribution of pedestrian contact.

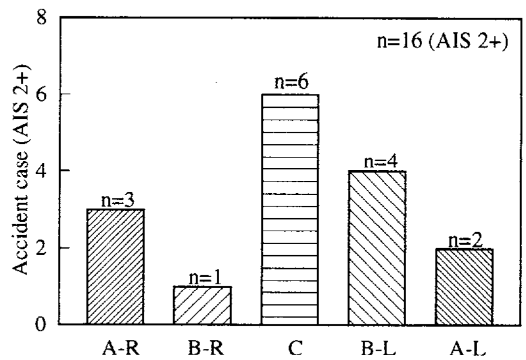


Figure 9. Distribution of pedestrian contact with AIS 2+ injury.

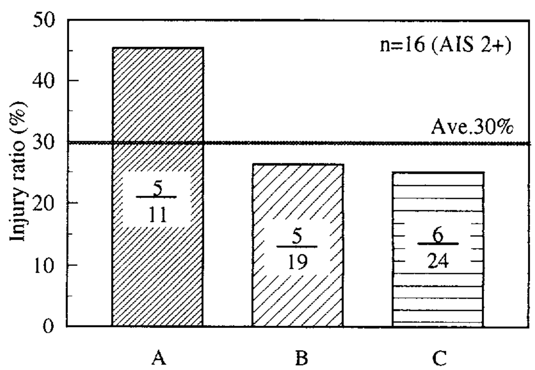


Figure 10. Injury ratio of AIS 2+ by contact location.

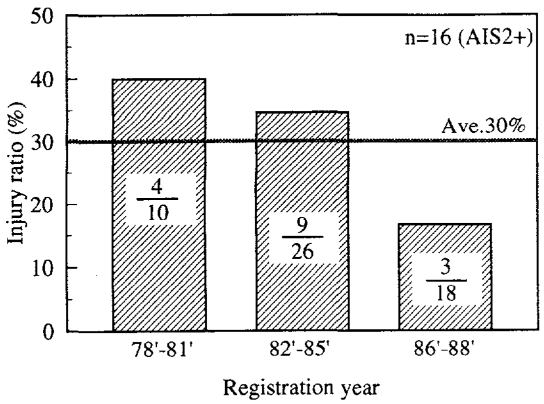


Figure 11. Injury ratio of AIS 2+ by vehicle registered year.

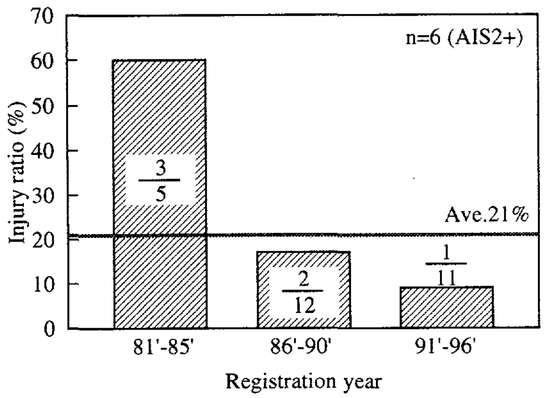


Figure 12. Injury ratio of AIS 2+ by vehicle registered year referred from ITARDA data [5].

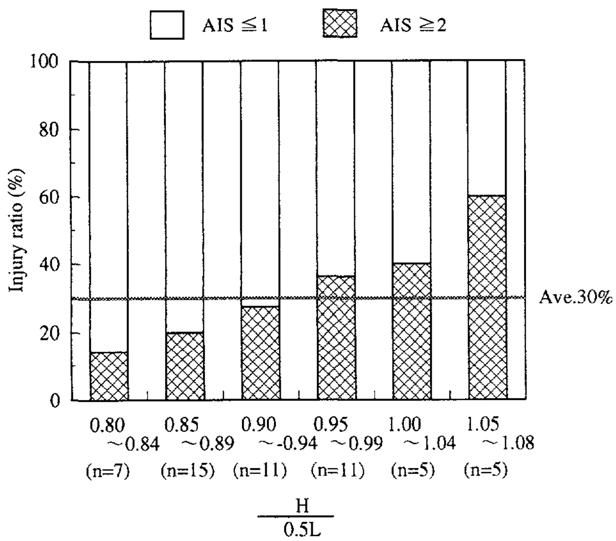


Figure 13. Injury ratio versus normalized bonnet leading edge height.

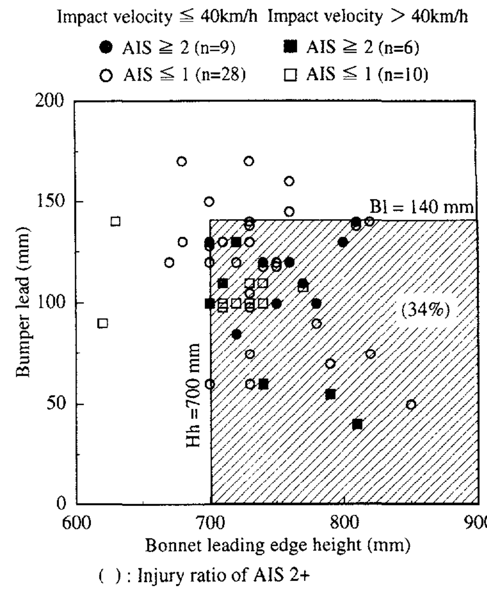


Figure 14. Distributions of all injuries by bonnet leading edge height and bumper lead.

Older vehicles had a higher risk of AIS 2+ compared to newer vehicles as shown in Figure 11. The registration year is almost comparable to model year.

When we referred to the latest pedestrian accident data [5], new model indicated a lower risk of AIS 2+ as shown in Figure 12.

For majority of adult pedestrians, the impact of the bonnet leading edge will be directly on the femur [6]. The effective height of the bonnet leading edge or wing may differ according to the pedestrian height. Consequently the injury risk by the normalized bonnet leading edge height (H / 0.5L) was obtained as shown in Figure 13. The normalized height was the ratio of the bonnet leading edge height (H) to the pedestrian hip joint height (0.5L). The hip joint height was assumed to be 50 % of the pedestrian stature (L). The injury ratio of AIS 2+ increased with the increase of the normalized bonnet leading edge height.

Distributions of All Injuries

The impact condition of the upper legform impact test are dependent on the bonnet leading edge height and the bumper lead. Figure 14 shows the distributions of all injuries by the bonnet leading edge height and the bumper lead. AIS 2+ injuries were located within the area of over 700 mm of the bonnet leading edge height and less than 140 mm of the bumper lead.

The normalized bonnet leading edge height (H / 0.5L) and the bumper lead affected the injury ratio of AIS 2+ as shown in Figure 15. The injury ratio was highest in the area of over 0.92 of the normalized bonnet leading edge height and less than 115 mm of the bumper lead. Each boundary line was determined considering about 50 percentile.

The pedestrian age and the vehicle registration year

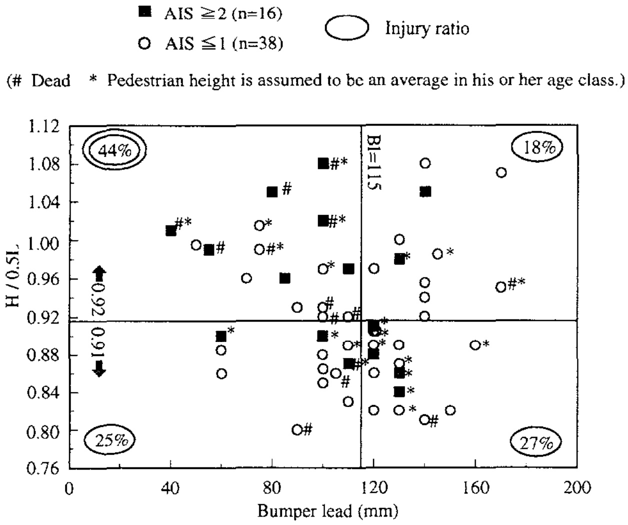


Figure 15. Distributions of all injuries by normalized bonnet leading edge height and bumper lead.

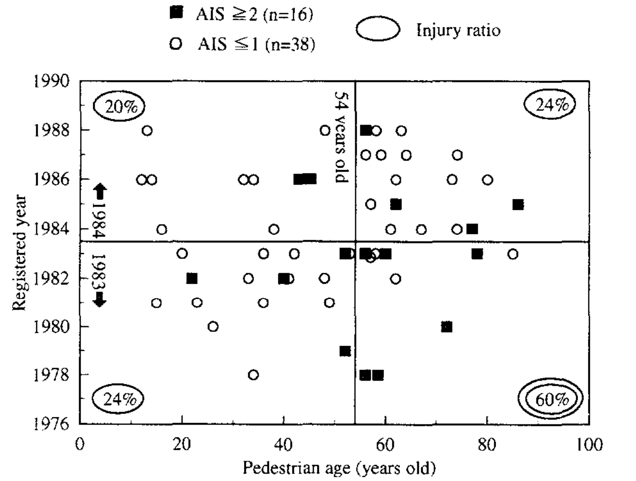
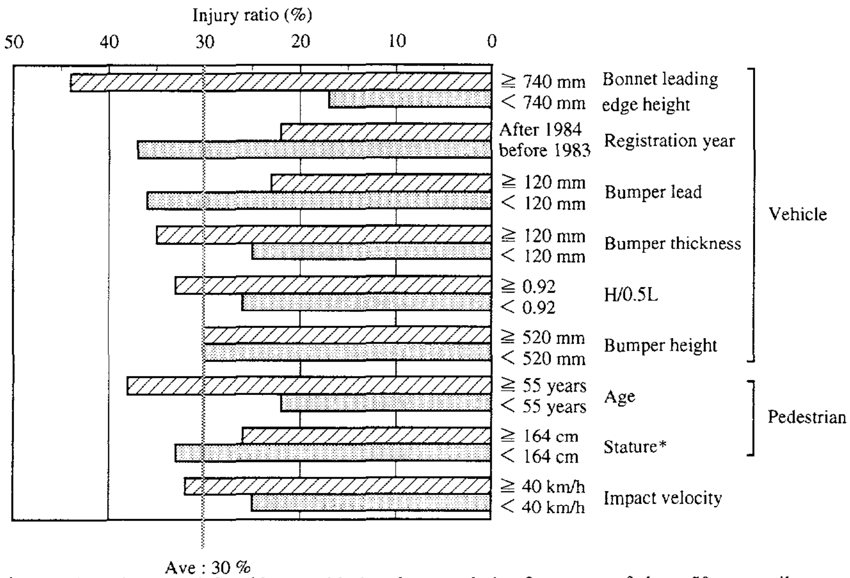


Figure 16. Distributions of all injuries by vehicle registration year and pedestrian age.



∴ Specific values are defined by considering the cumulative frequency of about 50 percentile.
* : 39 % of pedestrian stature is assumed to be an average in his or her age group.

Figure 17. Injury ratio by vehicle and pedestrian parameters.

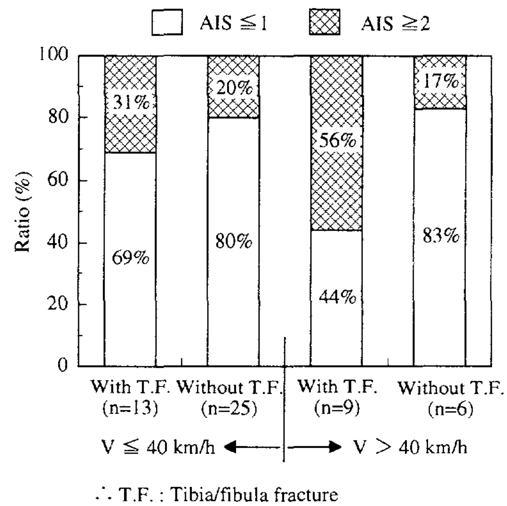


Figure 18. Constitution of femur/pelvis injury.

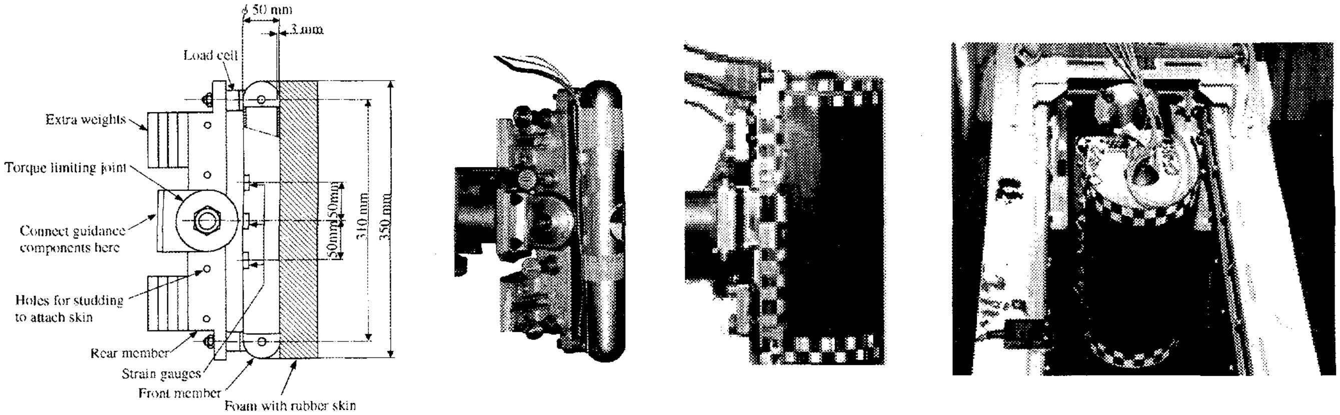
affected the injury ratio of AIS 2+ as shown in Figure 16. The injury ratio was highest for persons more than 54 years old and vehicles registered before 1983. The each boundary line was about 50 percentile.

The vehicle and pedestrian factors affecting the injury ratio of AIS 2+ are summarized in Figure 17. The top four factors affecting the injury risk of femur and pelvis were the bonnet leading edge height, the pedestrian age, the vehicle registration year and the bumper lead. The test condition of the upper legform impact test is determined from the bonnet leading edge height and bumper lead only. There seems to be other important factors to be considered in determining the test condition.

Influence of Lower Leg Fracture

In order to understand the influence of existence of tibia/fibula fractures on the injury severity of femur/pelvis, we conducted the following analyses.

For the two impact velocity groups and the two lower leg severity groups, the injury ratio of AIS 2+ femur/pelvis injury was obtained as shown in Figure 18. The severity of the upper leg injury has something to do with the severity of the lower leg injury. The upper leg injury severity may decrease if there is no fracture in the lower leg. This means that a pedestrian-friendly bumper could reduce the upper leg injuries.



Schematic **Side view** **Covered foam and skin** **Installed on propulsion system**

Figure 19. Upper legform impactor.

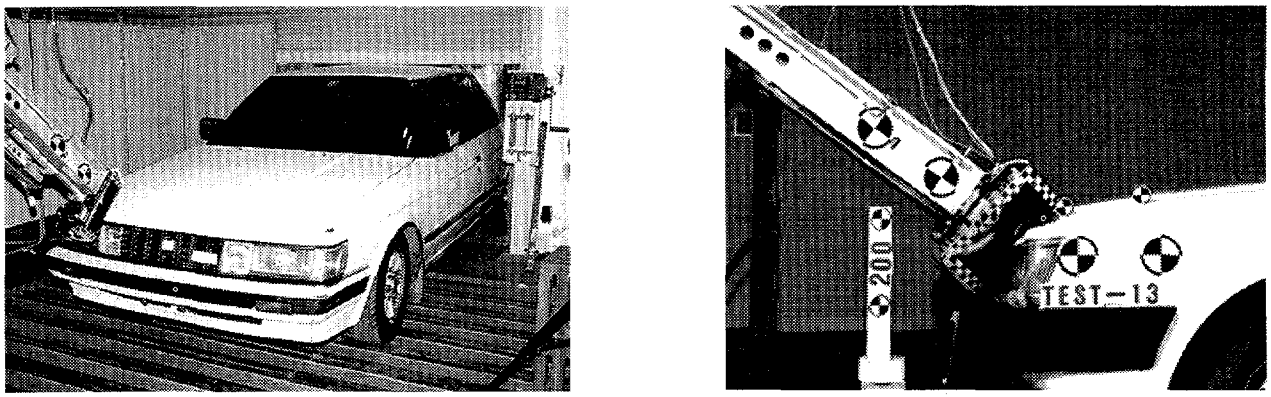


Figure 20. Upper legform to bonnet leading edge test.

EEVC UPPER LEGFORM IMPACT TEST

Pedestrian impact tests with production cars have been conducted according to the current EEVC method of the upper legform impact test in order to understand the reliability of this test procedure.

Methodology

EEVC/WG10 proposed a subsystem upper legform impact test method[1,7,8]. The aim of the upper legform to bonnet leading edge test is to evaluate the aggressiveness of the leading edge of the bonnet in causing femur/pelvis fractures.

Figure 19 shows the impactor developed by TRL. The impactor consists of a foam covered tube with three strain gauges (front member) and two load cells in between the front member and the rear member. Figure 20 shows the upper legform impact test. The vehicle with two 75 kg occupants is used to represent an impact at 40 km/h. The bonnet leading edge reference line is defined as shown in Figure 21. Figure 22 shows the impact condition. The impact velocity and the impact angle are determined with reference to Figures 23 and 24. The impactor mass (M) is calculated from Equation (1) with the impact velocity (V) and the energy (E). The energy is derived from Figure 25.

$$M = \frac{2E}{V^2} \qquad (1)$$

The upper legform impactor has been modified recently by TRL as shown in Figure 26. The initial design (type A) had inner and outer foam components (③, ④) and screws ⑦ intruding directly into the foam components. The type A caused a problem in measuring the impact force. The problem was considered to be an interaction between the foam components and screws. TRL then modified the type A and developed type B in which adapters ⑨ are inserted to prevent the interaction between the screws and the foam components. However, we found the type B still presents a problem in measuring the impact force.

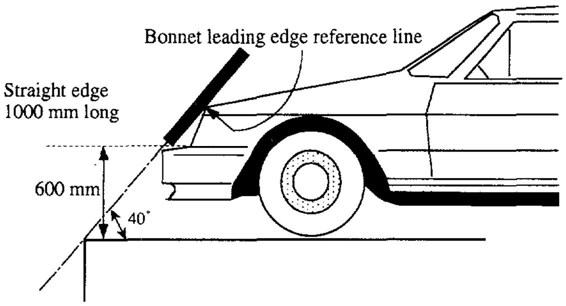


Figure 21. Bonnet leading edge reference line.

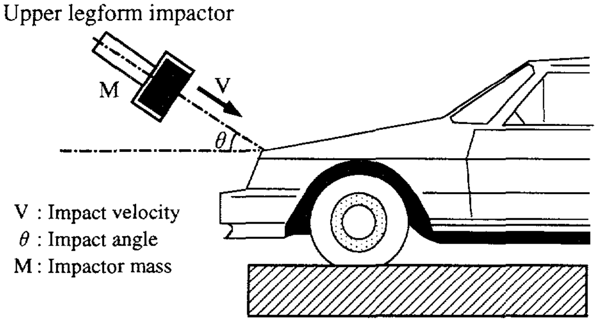
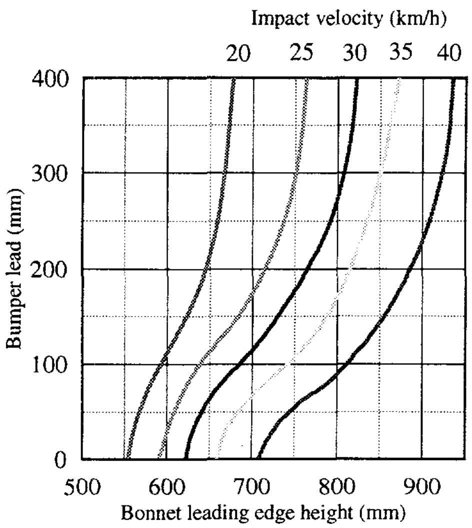
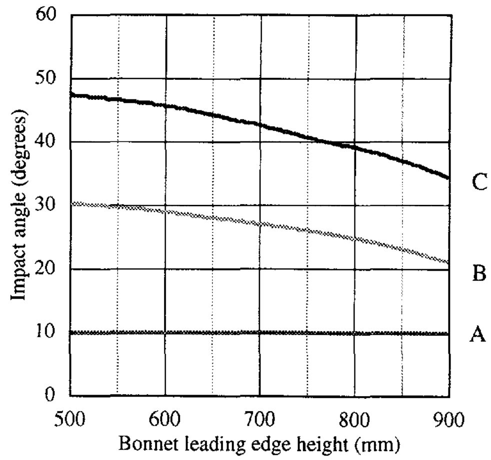


Figure 22. Impact condition.



Notes:
1. Interpolate horizontally between curves.
2. With configurations below 20km/h - test at 20km/h.
3. With configurations above 40km/h - test at 40km/h.
4. With negative bumper leads - test as for zero bumper lead.
5. With bumper leads above 400 mm - test as for 400mm.

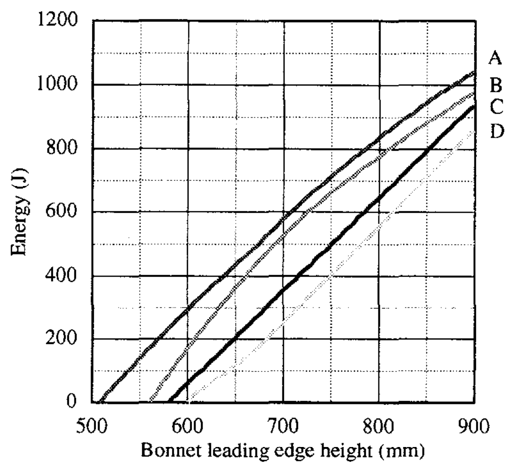
Figure 23. Impact velocity with respect to vehicle shape.



A ≦ 0 mm bumper lead
B = 50 mm bumper lead
C ≧ 150 mm bumper lead

Notes:
1. Interpolate horizontally between curves.
2. With negative bumper leads - test as for zero bumper lead.
3. With bumper leads above 150 mm - test as for 150mm.
4. With bonnet heights above 900 mm - test as for 900mm.

Figure 24. Impact angle with respect to vehicle shape.



A ≦ 0 mm bumper lead
B = 100 mm bumper lead
C = 225 mm bumper lead
D ≧ 350 mm bumper lead

Notes:
1. Interpolate horizontally between curves.
2. With negative bumper leads - test as for zero bumper lead.
3. With bumper leads above 350 mm - test as for 350mm.
4. With bonnet heights above 900 mm - test as for 900mm.

Figure 25. Impact energy with respect to vehicle shape.

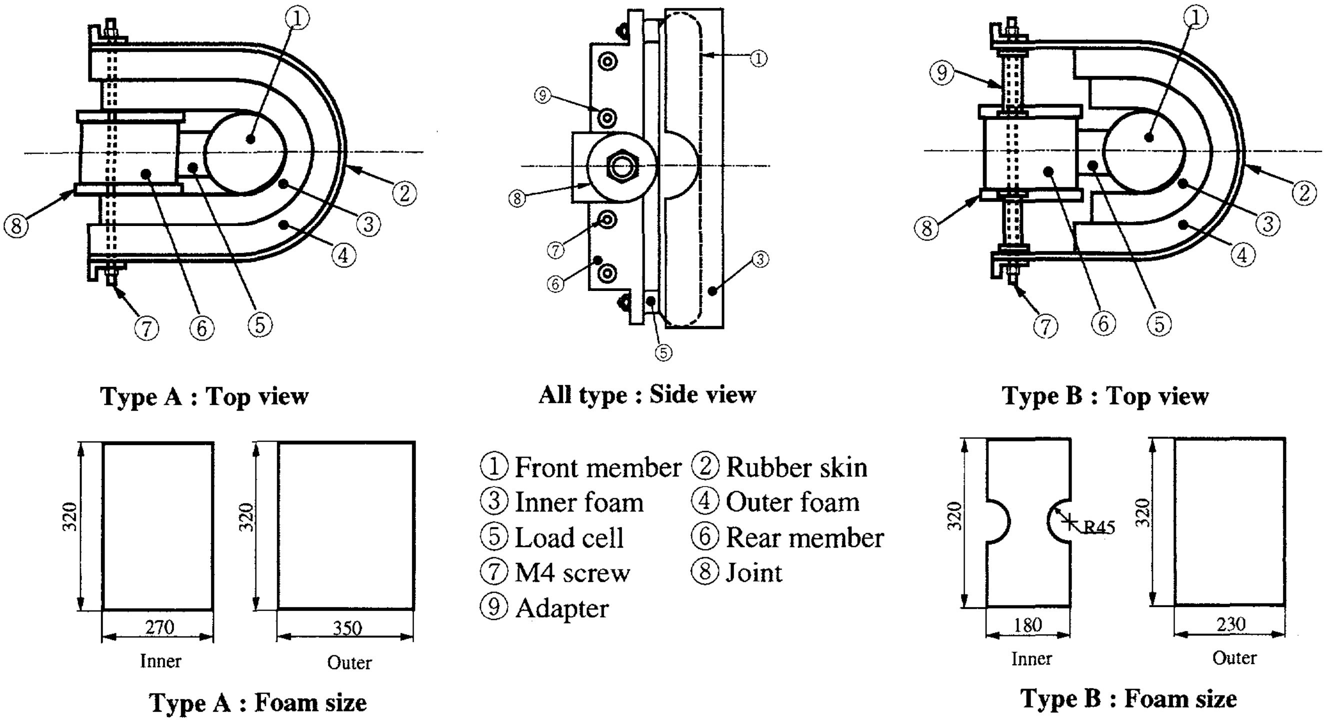


Figure 26. Modification of upper legform impactor.

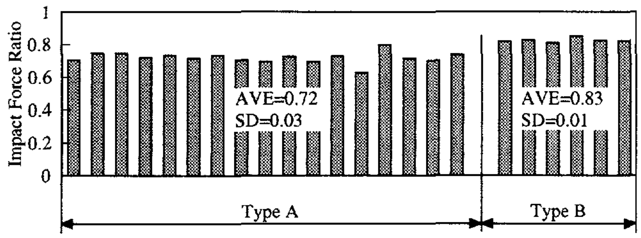


Figure 27. Impact force ratio in EEVC upper legform impact tests.

In measuring the impact force, load cells were recommended to be Kistler type 9021A piezo-electric [9]. Figure 27 shows the ratio of the peak impact force from the load cell to the inertia force calculated by the rear member mass and its acceleration. Theoretically the impact force ratio should be one. However the type A and type B do not reach the ratio of one. We use strain gauge load cells in order to improve the accuracy in measuring the impact force.

Test Results Using Production Cars

We conducted the upper legform impact test using 15 production cars. The current injury criteria is a total force of 4 kN and a bending moment of 220 Nm. Figure 28 shows the results from 19 tests comparing to the injury criteria. None of the test results met the requirement.

When we review the pedestrian accident data, the number of severe femur/pelvis injuries caused by the bonnet leading edge is smaller than that of other severe injuries caused by the bonnet or bumper. In contrast, the results from the three EEVC component tests with production cars indicated that the upper legform impact test had the most difficulty fulfilling the requirements of the current injury criteria. When we consider the priority of the pedestrian test procedure, the upper legform impact test should be the lowest

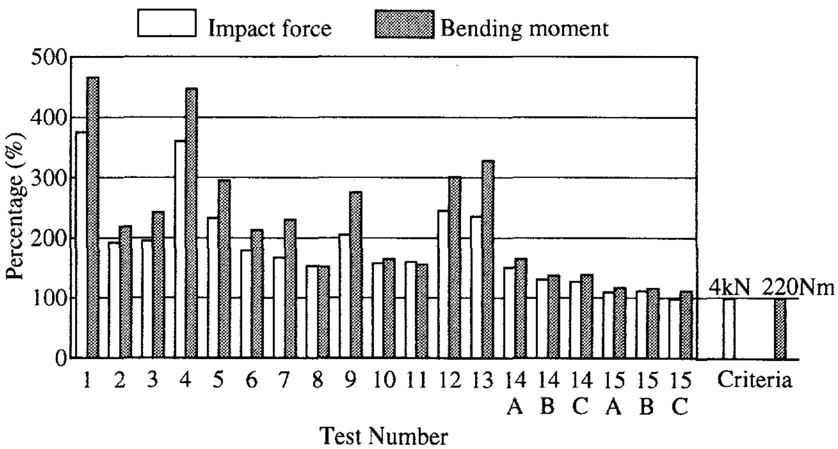


Figure 28. Results of EEVC upper legform impact tests.

among the three subsystem tests. The current injury criteria of the upper legform impact test does not reflect real world-pedestrian accidents. The current injury criteria were derived from the three accident reconstruction tests for AIS 3 cases by TRL [6].

Accordingly, we conducted accident reconstruction tests to validate the EEVC upper legform impact test and its injury criteria.

ACCIDENT RECONSTRUCTION TEST

The objective of this test is to validate the current injury criteria of the upper legform impact test proposed by EEVC/WG10 [8]. Using the upper legform impactor we reconstructed the vehicle damage and physical values related to pedestrian injuries induced by the leading edge of bonnet or wing.

Accident Data Selected

We selected 16 accident cases in which pedestrians were adults and a child with 150 cm stature from the JARI pedestrian accident data base. Table 2 lists the selected accident cases. The vehicle impact velocity is 40 ± 10 km/h for 15 cases and 25 km/h for 1 case. To evaluate physical value of different injury severities, AIS 2+ injury cases (6 cases) and no injury or AIS 1 injury cases (10 cases) were selected. The definition of injured part is shown in Figure 29.

Table 2.
Selected Accident Cases

Case	Car							Pedestrian						
	Impact velocity (km/h)	Model year	Frontal shape			Hoodedge damage		Sex	Age	Stature (cm)	Weight (kg)	Impact direction***	Injury of upper leg	
			B/L (mm)	Bh (mm)	H (mm)	Damage location*	凹 (mm)						AIS	Injury description
1	40	1983	85	570	780	B-L	0	F	78	-	-	F	3	Femur fracture
2	50	1985	30	560	810	A-R	5	M	62	-	-	L	3	Femur fracture
3	35	1982	120	510	770	C	20	M	22	168	58	L	2	Kidney damage
4	30	1979	130	480	800	C	50	M	52	-	-	R	2	Pelvic fracture
5	40	1986	155	490	705	C	20	F	80	-	-	L	1	Thigh contusion
6	25	1983	110	500	700	C	5	F	20	163	45	R	1	Thigh contusion
7	30	1983	140	520	730	A-L	10	M	58	158	52	B	1	Waist contusion
8	45	1982	105	525	690	B-L	30	M	33	160	63	F	1	Thigh contusion
9	30	1986	110	501	733	C	15	F	12	150	43	L	1	Waist contusion
10	35	1984	104	495	695	A-L	10	F	77	150	50	L	3	Femur fracture
													2	Pelvic fracture
11	35	1987	98	510	701	C	7	M	59	170	80	L	0	No injury
12	40	1984	160	492	759	C	10	M	38	175	70	R	0	No injury
13	40	1984	135	470	680	C	5	F	16	-	-	B	0	No injury
14	40	1986	113	506	734	B-L	10**	M	56	-	-	R	0	No injury
15	45	1986	146	444	657	B-L	10	M	45	-	-	L	2	Pelvic fracture
16	45	1984	114	498	698	C	10	F	67	-	-	B	0	No injury

* : See Figure 7.
** : The residual deformation is estimated from photograph.
*** : F ; Front, B ; Back, R ; Right, L ; Left

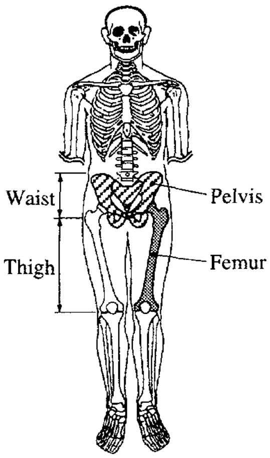


Figure 29. Definition of injury part.

Methodology

Two methods were used to conduct the reconstruction tests. One was essentially based on the EEVC (EEVC method) and the other, on the computer simulation (Simulation method).

In the EEVC method, the impact angle, impactor mass, and impact velocity were derived from the look-up graphs (See Figures 23, 24 and 25) according to the bonnet leading edge height and the bumper lead. When the accident impact speed was not 40 km/h, the impact velocity was compensated considering the speed ratio of the reported accident impact speed to 40 km/h.

In the Simulation method, the impact conditions were calculated using a validated car-pedestrian impact model [10]. The impact angle was calculated from the impact force vector when the impact force became maximum. The impact velocity was the relative velocity between the pedestrian and vehicle when they start to contact. Impact energy was obtained by integrating the impact force by the displacement of femur/pelvis until the impact force became maximum. The impactor mass can be calculated from the impact velocity and the impact energy by means of Equation (1). However, the impactor mass was fixed to be 20 kg in some test cases in order to understand the influence of impactor mass onto the physical values to be measured. In these cases, the impact velocity from the computer simulation was not used, and the impact velocity was adjusted by considering the mass ratio of the impactor under the given impact energy.

We conducted phase 1 reconstruction tests (accident cases 1 to 8) and phase 2 reconstruction tests (accident cases 9 to 16). In the phase 1 tests, only the EEVC method was used. In the phase 2 tests, both the EEVC method and the Simulation methods were used. A new bonnet was used in each test.

Results

A total of 12 accident cases was successfully reconstructed, but four cases were not. Table 3 summarizes the test conditions and results of all our reconstruction tests (32 tests). Typical cases in which there was good agreement, acceptable agreement, or disagreement are shown in Appendix A.

Using the EEVC method, only five out of 16 accident cases (31%) were reconstructed with good agreement as shown in Table 3. Case number 9 to 16 were reconstructed according to the EEVC and Simulation methods. By using the Simulation method, we reconstructed four out of 8 accident cases (50%) with good agreement. The EEVC upper legform impact test method still seems to be incomplete and needs further improvement to reflect real-world pedestrian accidents.

Through the reconstruction tests using the fixed impactor mass of 20 kg, we found that the impact energy was most important to reproduce the damage pattern of vehicle with the upper legform impactor. Impactor mass can be fixed. Impact velocity can be defined from the impact energy and the constant impactor mass without using an impact velocity look-up graph.

In order to understand the relationship between measured physical values and injury severity, 12 test cases or the best cases are selected from the accident reconstruction tests as shown in Table 4. Six cases are for AIS 2+, one case for AIS 1, and five cases for no injury.

To clarify the current injury criteria (4 kN, 220 Nm) relative to the injury severity, we plotted measured impact forces and bending moments with injury severity as shown in Figure 30. The test results clearly indicate that the current injury criteria means a 0 % possibility causing AIS 2+ injuries.

Figures 31 shows the cumulative frequency of impact forces and bending moments for two different injury severities (AIS 2+ and no injury or AIS 1). It should be noted that the measured impact forces and bending moments in AIS 2+ injuries are lower than those in no injury or AIS 1 injuries because a femur/pelvis fracture may affect the impact forces and bending moments. A femur/pelvis fracture mechanism was not incorporated when designing the upper legform impactor.

Table 5 summarizes the impact forces and the bending moments, in which some reference values are listed for minimum, maximum, average ± standard deviation, 20 percentile and 50 percentile. The EEVC current injury criteria were derived from an average value for AIS 3 accident cases [6]. The average impact forces and bending moments in AIS 2+ injuries are about twice as high as the current injury criteria.

Table 3.
Test Conditions and Results (32 Tests for 16 Accident Cases)

Accident			Reconstruction test										
Case	Car		Conditions					Results					Agreement of the hoodedge damage****
	Impact velocity (km/h)	[II] (mm)	Ped.-car impact vel.** (km/h)	Upper legform impactor				Hoodedge damage [II](mm)	Force (kN)	Bending moment			
				Velocity (km/h)	Angle (degree)	Energy (J)	Mass (kg)			Upper (Nm)	Middle (Nm)	Lower (Nm)	
1	40	0	25 [E]	20.8 {23.1}	29.5	232	13.9	1	7.4	386	542	525	○+
			40 [E]	38.3 {36.9}	29.5	787	13.9	20	14.4	741	981	916	×
2	50	5	20 [E]	19.1 {20.0}	18.0	187	13.3	5	5.2	333	395	375	○+
			25 [E]	24.4 {25.0}	18.0	305	13.3	11	6.9	479	545	459	△
			35 [E]	35.3 {35.0}	18.0	639	13.3	27	10.1	558	722	672	×
			40 [E]	40.1 {40.0}	18.0	825	13.3	35	15.0	849	1026	915	×
3	35	20	40 [E]	35.3 {35.5}	29.5	663	13.8	20	8.2	473	605	556	○+
4	30	50	40 [E]	38.0 {36.9}	35.0	774	13.9	36	7.7	479	467	321	△+
			35 [E]	32.9 {32.3}	35.0	580	13.9	32	6.8	456	455	309	△
5	40	20	40 [E]	25.9 {26.7}	41.5	424	16.4	21	6.8	348	384	311	×
			40 [E]	25.7 {26.7}	41.5	418	16.4	20	6.3	304	363	309	×
6	25	5	40 [E]	30.8 {30.5}	35.5	509	13.9	20	6.1	307	331	269	×
7	30	10	40 [E]	31.1 {30.5}	39.5	560	15.0	45	9.3	537	650	536	×
8	45	30	40 [E]	31.1 {30.5}	35.0	489	13.1	20	6.7	382	505	471	×
9	30	15	30 [S]	23.8 {23.4}	10.6	437	20.0	15	7.4	366	444	396	○+
			30 [E]	25.8 {24.9}	34.7	475	18.5	10	8.4	457	546	486	×
10	35	10	30 [S]	22.1 {21.2}	19.9	377	20.0	13	9.4	418	560	556	○+
			25 [S]	17.5 {17.7}	16.8***	236	20.0	11	5.8	213	278	286	△
			35 [E]	25.3 {26.7}	35.0	388	15.7	15	9.4	534	618	530	△
11	35	7	35 [E]	28.5 {27.6}	33.9	486	15.5	10	9.4	550	662	588	○+
			35 [S]	25.5 {26.8}	17.3	502	20.0	9	10.9	509	674	654	△
12	40	10	35 [S]	27.1 {27.5}	35.6	567	20.0	10	10.2	561	677	595	○+
			40 [E]	29.4 {31.8}	39.8	504	15.1	9	9.8	566	663	569	○
13	40	5	30 [S]	20.2 {18.9}	54.2	231	14.7	7	5.1	265	306	263	○+
			40 [E]	26.9 {26.0}	40.3	433	15.5	13	6.4	286	341	311	×
14	40	10*	40 [E]	31.1 {33.1}	35.1	520	13.9	9	9.4	567	721	672	△+
			30 [S]	23.0 {23.67}	14.2	408	20.0	5	10.8	515	698	679	×
15	45	10	45 [E]	26.3 {25.9}	42.7	363	13.6	13	6.6	326	429	404	△+
			45 [E]	28.4 {25.9}	42.7	423	13.6	13	6.3	334	438	412	△
			50 [S]	30.0 {30.9}	29.5	358	10.3	6	6.3	258	369	378	×
16	45	10	45 [E]	33.0 {33.7}	36.4	529	12.6	12	7.7	371	445	400	△+
			40 [S]	25.9 {24.0}	62.8	518	20.0	25	6.6	321	334	265	△

* : The residual deformation is estimated from photograph.
** : [E] ; EEVC method, [S] ; Simulation method.
*** : The impact angle should be 24.3 °.
**** : ○ ; Good agreement, △ ; Acceptable agreement, × ; Disagreement.
: + ; Best case in the accident reconstructions.

Table 4.
Summary of Accident Reconstruction Tests (12 Accident Cases)

#	Case	Pedestrian							Car				Reconstruction test results					Agreement
		Injury induced by hoodedge		Sex	Age	Height, L	Weight		Impact velocity	Frontal shape			Ped. - car impact velocity	Force	Bending moment			of the hoodedge damage
		AIS	Injury description			(cm)	(kg)		(km/h)	B/L (mm)	Bh (mm)	H (mm)	(km/h)	(kN)	Upper (Nm)	Middle (Nm)	Lower (Nm)	
1	1	3	Femur fracture	F	78	-	-		40	85	570	780	25 [E]	7.4	386	542	525	○
2	2	3	Femur fracture	M	62	-	-		50	30	560	810	20 [E]	5.2	333	395	375	○
3	10	3	Femur / pelvic fracture	F	77	150	50		35	104	495	695	30 [S]	9.4	418	560	556	○
4	3	2	Kidney damage	M	22	168	58		35	120	510	770	40 [E]	8.2	473	605	556	○
5	4	2	Pelvic fracture	M	52	-	-		30	130	480	800	40 [E]	7.7	479	467	321	△
6	15	2	Pelvic fracture	M	45	-	-		45	146	444	657	45 [E]	6.6	326	429	404	△
7	9	1	Waist contusion	F	12	150	43		30	110	501	733	30 [S]	7.4	366	444	396	○
8	11	0	No injury	M	59	170	80		35	98	510	701	35 [E]	9.4	550	662	588	○
9	12	0	No injury	M	38	175	70		40	160	492	759	35 [S]	10.2	561	677	595	○
10	13	0	No injury	F	16	-	-		40	135	470	680	30 [S]	5.1	265	306	263	○
11	14	0	No injury	M	56	-	-		40	113	506	734	40 [E]	9.4	567	721	672	△
12	16	0	No injury	F	67	-	-		45	114	498	698	45 [E]	7.7	371	445	400	△

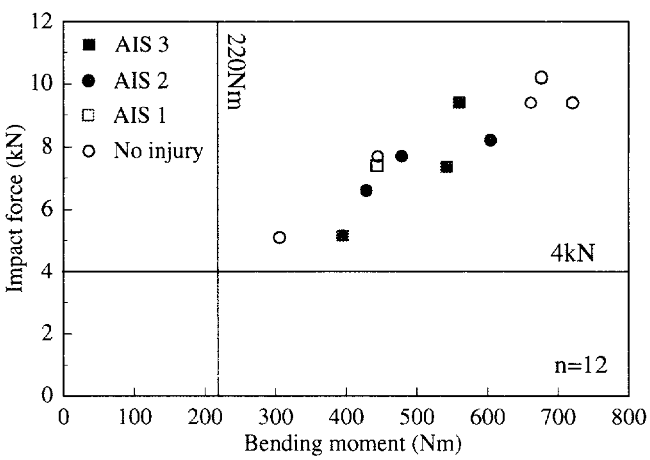
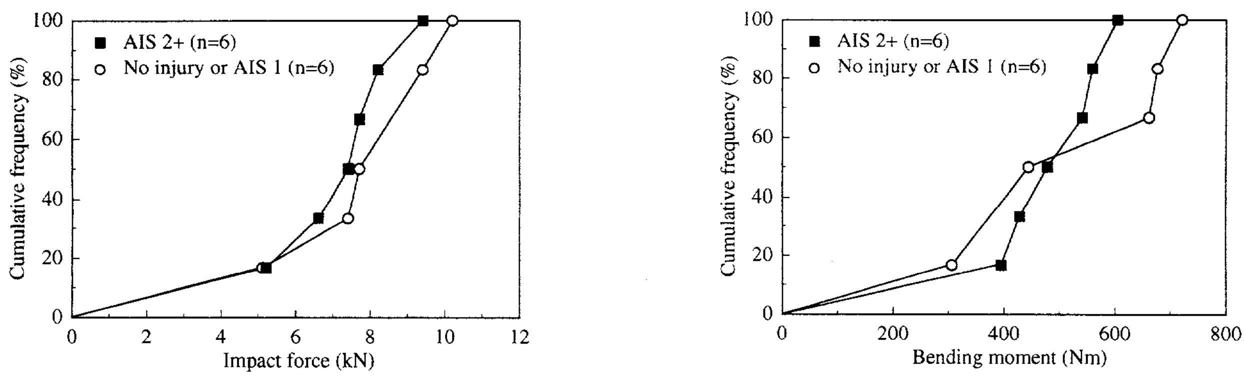


Figure 30. Impact force and bending moment with injury severity from accident reconstructions.



(1) Impact force **(2) Bending moment**

Figure 31. Cumulative frequency of physical value.

Table 5.
Summary of Impact Force and Bending Moment (12 Accident Cases)

Injury severity	cases	Measured impact force (kN)				
		Min.	Max.	Ave. ± SD	20 percentile	50 percentile
AIS 2+	6	5.2	9.4	7.4 ± 1.3	5.5	7.4
No injury and AIS 1	6	5.1	10.2	8.2 ± 1.7	5.6	7.7
Injury severity	**cases**	**Measured bending moment (Nm)**				
		Min.	Max.	Ave.	20 percentile	50 percentile
AIS 2+	6	395	605	502 ± 74	402	479
No injury and AIS 1	6	306	721	543 ± 152	334	445

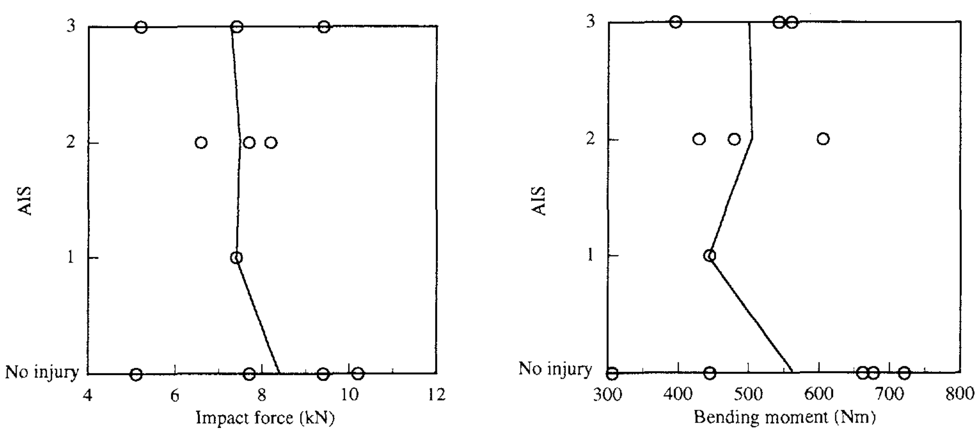
∵ 20 percentile and 50 percentile are obtained from the cumulative frequency curve (Figures 47 and 48).

DISCUSSION

The impact force and the bending moment related to each AIS level may also be presented as an injury risk curve as shown in Figure 32. The solid lines are on the average values in each AIS level. These lines show that the impact force and the bending moment tend to decrease with the increase of AIS. The measured impact forces and bending moments did not correlate to the significance of AIS severity (See Appendix B).

On the contrary, in case of the head injury criteria (HIC), HIC values increase according to the significance of AIS severity [11]. If the upper legform impact test is appropriate to reconstruct the femur/pelvis injuries, the measured impact force and bending moment could increase with the increase of AIS.

This contradiction may raise questions of whether the current upper legform impact test reflects the real world pedestrian accidents.



(1) Impact force **(2) Bending moment**

Figure 32. Physical value versus injury severity.

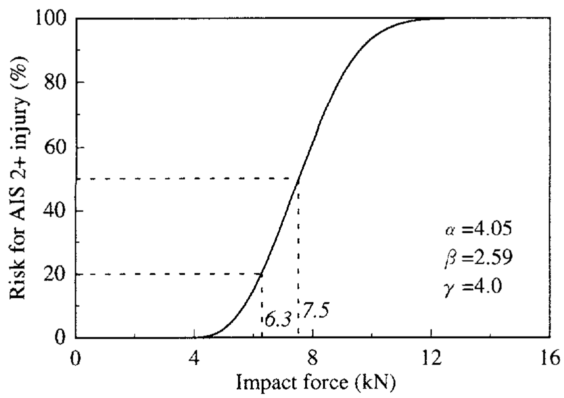
A biomechanical injury risk curve describing the relationship between the injury level and its corresponding physical value is necessary to propose the injury criteria for the upper legform impact test. To establish the injury criteria for femur/pelvis AIS 2+ injuries, we made a Weibull cumulative frequency curve from the accident reconstruction tests as shown in Figure 33. The Weibull curve with one variable and three parameters is defined as follows;

$$W(z;\alpha,\beta,\gamma) = 1 - e^{-\left(\frac{z-\gamma}{\alpha}\right)^{\beta}} \quad (2)$$

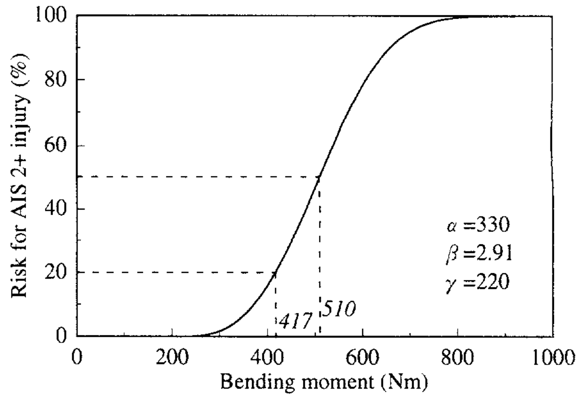
Where
Z is independent variable,
α is the scale parameter,
β is the shape parameter, and
γ is the location parameter.

The scale and shape parameters were chosen based on the impact force and bending moment causing the AIS 2+ injury. The location parameter was decided to be 4 kN and 220 Nm with 0 % probability of causing an AIS 2+ injury (See Figure 30).

Head Injury Criteria (HIC) 1000 means about a 20 % probability of death [12]. A femur/pelvis fracture is not commonly a life threatening injury. Accordingly, the probability of the femur/pelvis AIS 2+ injury can be raised to 50 %. For a 50 % femur/pelvis injury risk with AIS 2+, the impact force is 7.5 kN and the bending moment is 510 Nm. For a 20 % risk, the impact force is 6.3 kN and the bending moment is 417 Nm.



(1) Impact force



(2) Bending moment

Figure 33. Weibull injury risk curve.

CONCLUSIONS

Pedestrian accident analysis and accident reconstruction test were conducted to validate the EEVC pedestrian upper legform impact test. Conclusions are summarized below.

(1) The pedestrian accident data indicated the related injury of femur and pelvis with AIS 2+ caused by the leading edge of the bonnet and wing decreased by 50 % during the last ten years.

(2) Recent accident analyses indicate that the priority of the upper legform impact test seems to be the lowest in the three EEVC subsystem tests. However, the upper legform impact test had the most difficulty fulfilling the requirement of the current injury criteria among the three EEVC pedestrian tests.

(3) In pedestrian accident, the top four factors affecting the injury of femur and pelvis were the bonnet leading edge height, the pedestrian age, the vehicle registration year, and the bumper lead.

(4) The upper leg injury severity may decrease if there is no fracture in the lower leg. This means that a pedestrian-friendly bumper will reduce the upper leg injuries.

(5) The biomechanical injury risk curve for the upper legform impact test was obtained from the accident reconstruction tests using the Weibull cumulative frequency curve. For the 50 percentile injury risk of femur and pelvis with AIS 2+, the impact force is 7.5 kN and the bending moment is 510 Nm.

(6) Physical values used as injury criteria should correlate to the significance of injury severity. However, the measured impact force and bending moment did not increase with the significance of AIS severity. This contradiction raises questions of whether the current injury criteria and method of the upper legform impact test are valid.

(7) Impact energy was most important to reconstruct the damage pattern of vehicle with the upper legform impactor. Constant mass can be used for the impactor. Impact velocity can be defined from the impact energy and the constant impactor mass without using an impact velocity look-up graph.

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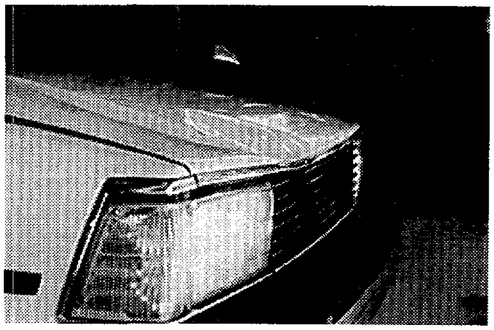
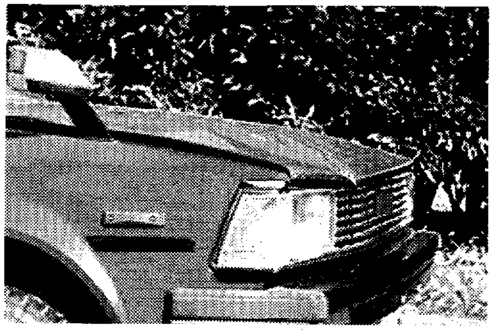
APPENDIX A



Accident

Residual deformation : 20 mm
Ped-car impact vel. : 35 km/h



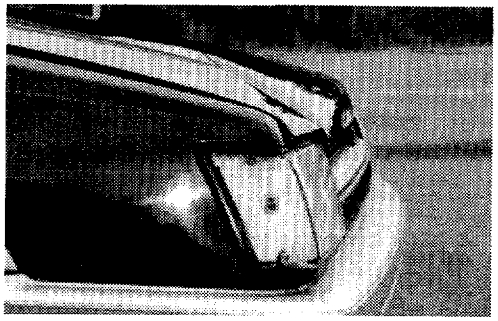
Test

Residual deformation : 20 mm
Ped-car impact vel : 40 km/h [E]
Impact angle : 29.5 deg.

Figure A-1. Good agreement case (case number 3).

Accident

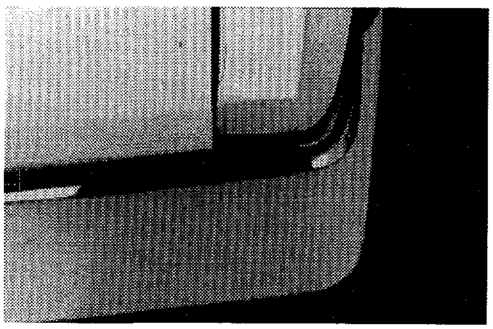
Residual deformation : 10 mm
Ped-car impact vel : 45 km/h



Test

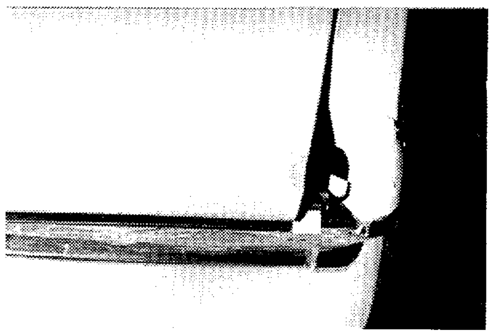
Residual deformation : 12 mm
Ped-car impact vel : 45 km/h [E]
Impact angle : 36.4 deg.

Figure A-2. Acceptable agreement case (case number 16).



Accident

Residual deformation : 10 mm
Ped-car impact vel : 30 km/h



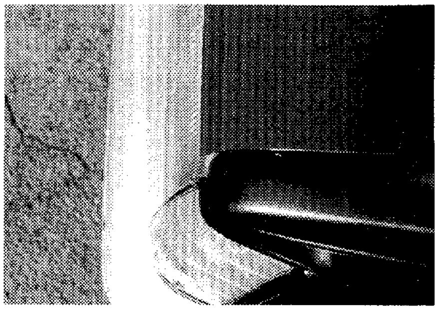
Test

Residual deformation : 45 mm
Ped-car impact vel : 40 km/h [E]
Impact angle : 39.5 deg.

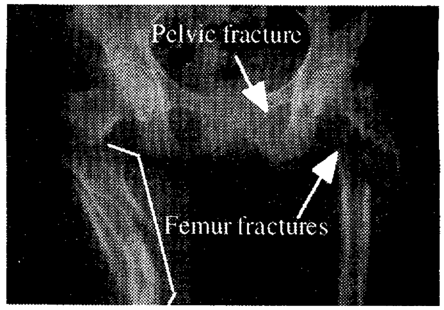
Figure A-3. Disagreement case (case number 7).

APPENDIX B

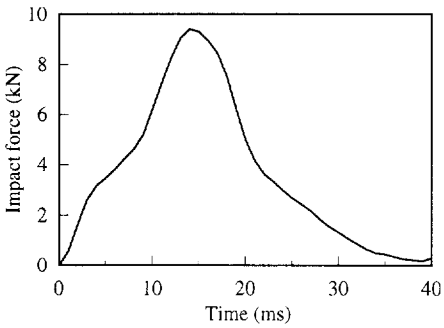
Accident



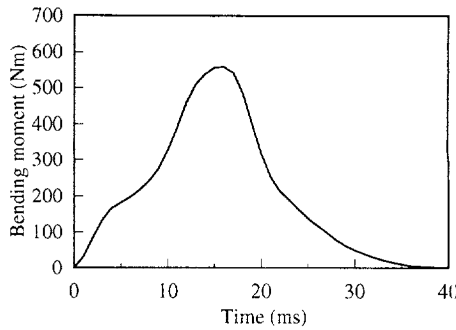
Test



Femur/pelvis fractures in an accident

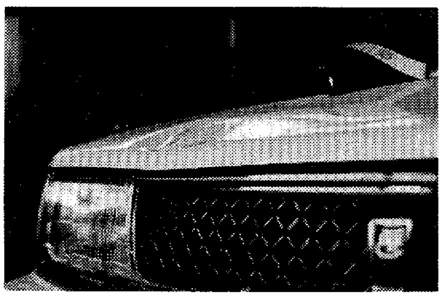


Impact force

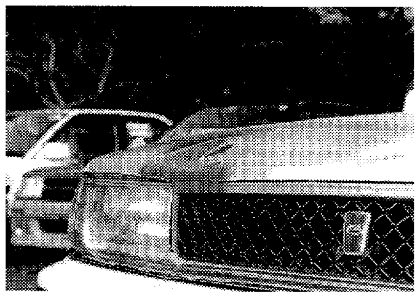


Bending moment

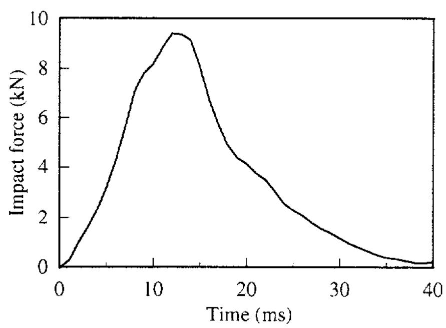
Figure B-1. AIS 2+ injury (fracture of femur and pelvis) case in good agreement (case number 10).



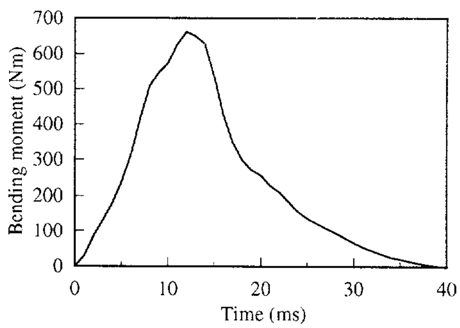
Accident



Test



Impact force



Bending moment

Figure B-2. No injury case in good agreement (case number 11).